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An analysis of the transient forces acting on Savonius rotors with different aspect ratios

Placide Jaohindy [a,*], Sean McTavish [b], François Garde [a], Alain Bastide [a]

[a] Physics and Mathematical Engineering Laboratory for Energy and Environment (PIMENT), University of Réunion Island, South Campus, 117 Avenue du Général Ailleret, 97430 Le Tampon, France

[b] Dept. of Mechanical and Aerospace Engineering, Carleton University, 1125 Colonel By Drive, Ottawa, Ontario, Canada K1S 5B6

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ABSTRACT

The present study deals with the analysis of the transient forces of a Savonius vertical axis wind turbine (VAWT) using computational fluid dynamics (CFD). Unsteady, Reynolds Averaged Navier–Stokes CFD simulations were conducted using two different rotors and two simulation methodologies. The first rotor had an aspect ratio of 1.1 and simulations were conducted by incorporating the dynamic equations of the rigid-rotor motion using a one degree-of-freedom (1-DOF) module to evaluate the rotor's free motion. The second rotor had an aspect ratio of 0.7 and simulations were conducted by specifying a fixed rotational velocity. The predicted torque and power curves were validated using experimental data. The transient forces from the two rotor blades, the resultant forces, and the longitudinal drag and lateral lift coefficients were evaluated using the two complementary data sets. The lateral force coefficient had a large contribution to the rotor torque at low azimuth angles and at low tip speed ratios (λ). At tip speed ratios above 0.6, the effect of the longitudinal drag force on the rotor operation increased and the lateral lift force contribution decreased. The resultant force angle was shown to become more acute due to the increase in the longitudinal force with increasing λ.

1. Introduction

The modeling of the motion and behavior of a vertical axis wind turbine (VAWT) is a technique widely used in the wind energy sector. This is a technique that is necessary to deepen the knowledge of the operation, control, structural stability, and performance of this type of wind turbine, which becomes increasingly popular [1]. The research effort at this level is conducted in order to have a more reliable and efficient wind turbine [2]. The modern VAWTs currently integrated in the urban area are exploited to maximize the security of the energy supply. Nowadays, the development of the wind energy system depends on the research effort spent on analytical and numerical methods. The numerical modeling and simulation of the airflow passing through a Savonius rotor is a physical problem taking into account the nature of the three-dimensional flow field around a rotating bluff body.

The Savonius rotor is an S-shaped VAWT that is simple in structure, operates at low speeds and accepts wind from any direction [2]. It is a VAWT that was originally proposed by a Finnish inventor [3]. The Savonius rotor has low construction costs, and is mainly employed for pumping water or producing wind power at a small scale [4]. The low rotational speed is the main cause of its low noise emissions. Its mechanical and aerodynamic characteristics make it suitable for the high turbulence intensity experienced in the urban area. A number of Savonius rotor experiments are available in literature [5,6]. The conventional Savonius rotor has a high starting torque and this particularity is an advantage for this kind of wind turbine [5], as they are often applied for starting torques for other VAWTs [7]. The work of Al-Bahadly [8] demonstrated that the number of rotor blades has a direct effect on the performance of the rotor. A Savonius rotor designed with three-blades generates favorable torque characteristics. However, it has a poor maximum power coefficient compared to the VAWT with two blades [2,9,10]. Menet affirmed that a two-stage Savonius rotor develops improved torque and power coefficients in comparison to the rotor in a single stage [10]. In the present work, a Savonius rotor with two blades and a single stage is modeled for simplicity of the rotor geometry and because it is the most commonly-studied type of Savonius rotor.

In this article, a dynamic study was conducted to simulate the transient behavior of the Savonius rotor. It consists of investigating the aerodynamic parameters of the VAWT using CFD methods. Three-dimensional numerical investigations of the aerodynamic

* Corresponding author.
E-mail address: placide.jaohindy@univ-reunion.fr (P. Jaohindy).

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Nomenclature

A	swept area
β	resultant force angle
C_P	power coefficient
C_{res}	resultant coefficient
C_t	torque coefficient
C_x	longitudinal force coefficient
C_y	lateral force coefficient
C_1	blade 1 force coefficient
C_2	blade 2 force coefficient
D	diameter
Δt	time step
e	overlap
f_r	ramping factor
F_x	longitudinal force
F_y	lateral force
F_1, F_2	blade forces
G_{oz}	external force
J_{ox}, J_{oy}, J_{oz}	principal moments of inertia
J_{xy}	product of inertia
λ	tip speed ratio
M_f	external moment
M_p	moment of pressures
M_t	rotor torque
M_τ	moment of viscous stresses
P	power
θ	azimuth angle
$\ddot{\theta}$	angular acceleration
Re_D	Reynolds number
T	simulation time
U	freestream velocity
ω	rotational velocity
X	longitudinal coordinate
Y	lateral coordinate

behavior of two Savonius wind turbines with different aspect ratios were conducted. The dynamic study of a VAWT with constant speed is the technique widely used in the wind energy domain [11–15]. Yet, few references in literature discuss the dynamic study of a Savonius rotor operating in free motion [16]. One of the rotors in this article was modeled using the free motion method proposed by d'Alessandro et al. [16], which modeled a Savonius rotor coupled with Matlab software. The other rotor simulation, however, imposed a constant rotational velocity. The modeling problems in the current study are implemented in two separate commercial codes, CD-Adapco Star-CCm+ and CFdesign 2010 [17,18].

While many experiments have investigated the dynamic torque and power [4] or static forces [19] generated by Savonius rotors, the behavior of the transient forces generated by Savonius rotors is not fully understood. The unsteady forces acting on the rotor will have implications related to the structural design of in-service rotors. Additionally, the transient lateral lift and longitudinal drag forces have not been explicitly treated in literature. The relative contributions of these forces throughout a revolution may help to develop a more complete understanding of the torque generation mechanisms of Savonius-type VAWTs. The simulations presented in this paper aim to treat these transient forces using complementary data from two Savonius rotors.

This article is divided into three main parts. The first part discusses the computational domains: their geometries, meshes and initial conditions. The second part then develops the strategy exploited to simulate the fluid rigid-rotor coupling. The final part presents the validation of the numerical models with experimental test cases found in literature. In addition to this, a numerical prediction of the forces acting on the two rigid-rotor blades and the resultant force acting on the rotors was performed. The longitudinal drag (C_x) and lateral lift (C_Y) coefficients were calculated and this work attempts to quantify the importance of each of these parameters throughout the operational range of a Savonius rotor.

2. Computational description

2.1. Savonius rotor geometry

Representative isometric and cross-sectional views of the Savonius rotors used in this study are presented in Fig. 1(a) and (b), respectively. Both rotors included circular end plates, as indicated in Fig. 1(a), although these are omitted in Fig. 1(b) for clarity. The

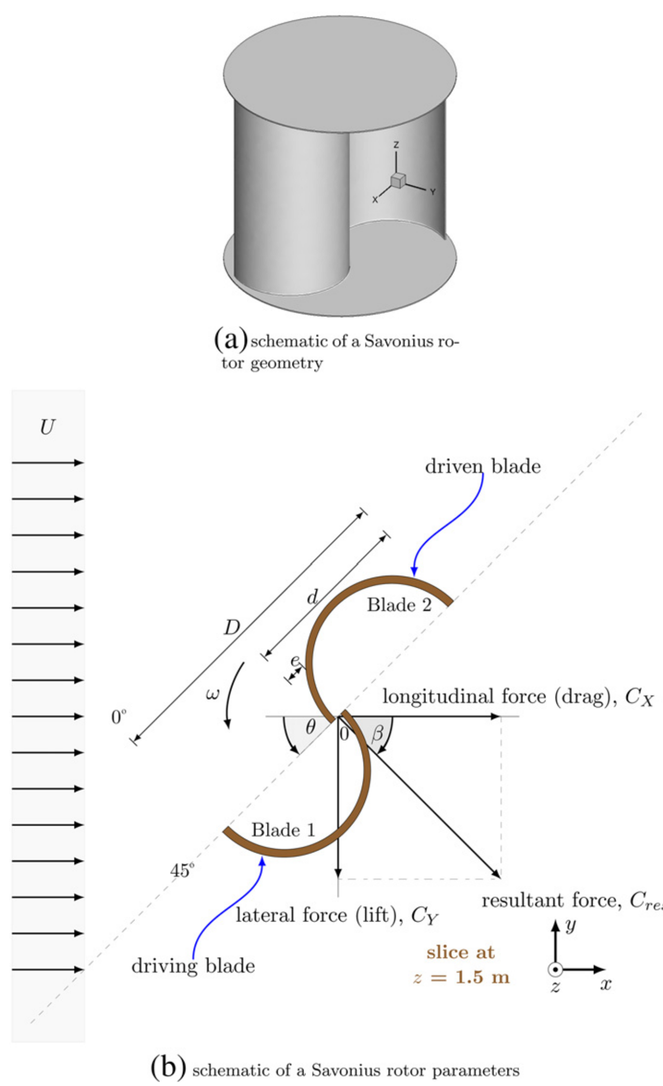

Fig. 1. Sketch and geometric parameters of the Savonius rotor.